

# Conformal Barrier for New Vector Bosons Decay to the Higgs

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The ATLAS collaboration has recently reported excesses about 2.5 sigma at mass around 2 TeV in the diboson channels, which can be identified with new vector bosons as a hint for the new physics. It is shown that spontaneously broken conformal/scale symmetry prohibits new vector bosons decay to the Higgs, which is contrasted to the popular “equivalence theorem” valid only in a special limit not necessarily relevant to the 2 TeV mass. If the decay  $V \rightarrow WH/ZH$  is not observed in the ongoing Run II of the LHC, then the 125 GeV Higgs can be a dilaton.

After the Higgs boson was discovered at LHC, there have been detailed LHC analyses of the Higgs, which is consistent with the standard model so far [1, 2], without serious hints for the new physics beyond the standard model. However, the origin of the mass of the Higgs itself is still a biggest mystery of modern particle physics, which would imply new physics beyond the standard model.

Very recently, the ATLAS collaboration [3] has reported excesses about 2.5 sigma (at global significance) with narrow width less than 100 GeV at mass around 2 TeV in the diboson channels <sup>#1</sup>. If it is confirmed in the LHC Run II, it will certainly be an outstanding signature of new physics. It should be deeply connected with the long-standing mystery, such as the naturalness, of the dynamical origin of the Higgs itself. Hence the events not only are exciting in their own right but also would be important to giving important clues to understand the nature of the Higgs.

With such excitements, the diboson events have already attracted a lot of attention proposing possible candidates for the origin of the excess, such as a new vector boson ( $V$ ) like technirhos [5, 6],  $W'/Z'$  [7–19], or others [20]. Most of such 2 TeV vector resonance models involves the vector boson decays to weak boson pairs ( $WW, WZ$ ), as well as the decays along with the 125 GeV Higgs ( $WH, ZH$ ). The ratio of the two decay rates is almost one,  $\Gamma(V \rightarrow WW/WZ)/\Gamma(V \rightarrow WH/ZH) \simeq 1$ , according to the popular “equivalence theorem”, see e.g., [7]. Hence one naively expects to discover the  $V$  not only in the  $WW/WZ$  channels, but also in the  $WH/ZH$  channels. Therefore the present CMS experimental bounds [21, 22] on the latter processes have already given stringent constraints on the generic vector models.

In this Letter we propose a novel way to identify the

dynamical origin of the 125 GeV Higgs through checking the possible decays of the 2 TeV new bosons. If the 2 TeV new bosons have no decays to the SM gauge bosons plus the 125 GeV Higgs then we show that the 125 GeV Higgs can be a dilaton, pseudo Nambu-Goldstone boson of the spontaneously broken conformality/scale symmetry of some underlying new physics, with the scale symmetry broken also explicitly only by the Higgs mass in the effective theory. One such an explicit example of the underlying theory is the walking technicolor [23] where the 125 GeV Higgs and the new bosons have been successfully identified with the technidilaton [24–29] and the walking technirho [5], respectively.

We begin with a generic model, called heavy-vector triplet (HVT) model [30], which is quoted by the ATLAS and CMS groups for new vector boson searches as a benchmark. The model Lagrangian reads [30]

$$\begin{aligned} \mathcal{L}_V = & -\frac{1}{2}\text{tr}[V_{\mu\nu}^2] + m_V^2\text{tr}[V_\mu^2] \\ & + g_V c_H (iH^\dagger V^\mu D_\mu H + \text{h.c.}) \\ & + 2g_V^2 c_{VVHH} \text{tr}[V_\mu^2] H^\dagger H \\ & + \mathcal{L}_{\text{Higgs}} + \dots, \end{aligned} \quad (1)$$

where we have put the standard-model Higgs terms  $\mathcal{L}_{\text{Higgs}}$  including the kinetic term  $|D_\mu H|^2$  and the usual Higgs potential ( $V_{\text{Higgs}}$ ). In Eq.(1) we have defined  $V_{\mu\nu} = D_\mu V_\nu - D_\nu V_\mu$  with  $D_\mu V_\nu = \partial_\mu V_\nu - ig_W[W_\mu, V_\nu]$  with the  $g_W$  being the weak gauge coupling. and have not displayed terms which do not include the Higgs  $H$  along with the new vector boson field  $V$ .

When the Higgs field  $H$  gets the vacuum expectation value  $v$  ( $\simeq 246$  GeV), the new vector boson  $V$  starts to mix with the weak boson  $W$  through the  $c_H$  term in Eq.(1). Parameterizing the  $H$  as  $H = v/\sqrt{2}(1 + \phi/v)(0, 1)^T$  plus the eaten Nambu-Goldstone boson terms and ignoring the hypercharge gauge for simplicity, one finds the mass matrix for  $\mathbf{V}_\mu = (V_\mu, W_\mu)^T$ ,

$$\mathcal{M}^2 = \begin{pmatrix} m_V^2 + g_V^2 c_{VVHH} v^2 & \frac{1}{4} g_W g_V c_H v^2 \\ \frac{1}{4} g_W g_V c_H v^2 & \frac{1}{4} g_W^2 v^2 \end{pmatrix}. \quad (2)$$

<sup>#1</sup> Small excesses about  $\sim 2$  sigma in the same mass region have been seen also in the CMS diboson analysis [4].

In addition, one has the Higgs ( $\phi$ ) couplings to  $V$  and  $W$ ,

$$\mathcal{G}_{VW\phi} = \begin{pmatrix} g_V^2 c_{VVHH} v^2 & \frac{1}{4} g_W g_V c_H v^2 \\ \frac{1}{4} g_W g_V c_H v^2 & \frac{1}{4} g_W^2 v^2 \end{pmatrix}. \quad (3)$$

In the Lagrangian the  $\mathcal{M}^2$  and  $\mathcal{G}_{VW\phi}$  terms look like

$$\mathcal{L}_V = \frac{1}{2} \mathbf{V}_\mu^T \cdot \mathcal{M}^2 \cdot \mathbf{V}^\mu + \frac{\phi}{v} \cdot \mathbf{V}_\mu^T \cdot \mathcal{G}_{VW\phi} \cdot \mathbf{V}^\mu - V_{\text{Higgs}} + \dots \quad (4)$$

Note that the mass matrix  $\mathcal{M}^2$  and the couplings to the Higgs  $\phi$  differ only by the  $m_V^2$  term. After diagonalizing the mass matrix Eq.(2), one gets the mass eigenstates  $\tilde{\mathbf{V}} = (\tilde{V}, \tilde{W})$  and finds the couplings such as  $\tilde{V}$ - $\tilde{V}$ - $\phi$ ,  $\tilde{W}$ - $\tilde{W}$ - $\phi$ , as well as the off diagonal coupling  $\tilde{V}$ - $\tilde{W}$ - $\phi$ . The presence of the nonzero off-diagonal coupling  $\tilde{V}$ - $\tilde{W}$ - $\phi$  is essentially due to the  $m_V^2$  term in Eq.(1): without the  $m_V^2$  term two mixing matrices  $\mathcal{M}^2$  and  $\mathcal{G}_{VW\phi}$  would become identical to be diagonalized simultaneously, so the  $\tilde{V}$ - $\tilde{W}$ - $\phi$  coupling would completely be rotated away.

Now, we shall introduce the conformal/scale invariance into the HVT model in Eq.(1). Examining terms in Eq.(1) in quadratic order of the vector fields with the scale dimensions taken into account, one readily realizes that only the  $m_V^2$  term violates the scale invariance for the action corresponding to the model Lagrangian Eq.(1) <sup>#2</sup>. Absence of this term does not affect 2 TeV mass of the new boson. Eliminating the  $m_V^2$  term, the conformal/scale invariance thus leads to the mass matrix

$$\mathcal{M}_{m_V=0}^2 = \begin{pmatrix} g_V^2 c_{VVHH} v^2 & \frac{1}{4} g_W g_V c_H v^2 \\ \frac{1}{4} g_W g_V c_H v^2 & \frac{1}{4} g_W^2 v^2 \end{pmatrix}. \quad (5)$$

This is the same matrix as the  $\mathcal{G}_{VW\phi}$  in Eq.(3), hence the off-diagonal  $\tilde{V}$ - $\tilde{W}$ - $\phi$  coupling goes away after the diagonalization of the vector boson sector:

$$\begin{aligned} \mathcal{L}_V \Big|_{m_V=0} &= \frac{1}{2} \mathbf{V}_\mu^T \cdot \mathcal{M}_{m_V=0}^2 \cdot \mathbf{V}^\mu + \frac{\phi}{v} \cdot \mathbf{V}_\mu^T \cdot \mathcal{G}_{VW\phi} \cdot \mathbf{V}^\mu \\ &+ \dots \\ &= \frac{1}{2} \left(1 + \frac{2\phi}{v}\right) \mathbf{V}_\mu^T \cdot \mathcal{M}_{m_V=0}^2 \cdot \mathbf{V}^\mu \\ &+ \dots \end{aligned} \quad (6)$$

In terms of the mass eigenstate fields  $\tilde{\mathbf{V}}_\mu = (\tilde{V}_\mu, \tilde{W}_\mu)^T$ , the Lagrangian Eq.(6) goes like

$$\begin{aligned} \mathcal{L}_V \Big|_{m_V=0} &= \frac{1}{2} \left(1 + \frac{2\phi}{v}\right) \tilde{\mathbf{V}}_\mu^T \cdot \begin{pmatrix} m_{\tilde{V}}^2 & 0 \\ 0 & m_{\tilde{W}}^2 \end{pmatrix} \cdot \tilde{\mathbf{V}}^\mu \\ &+ \dots, \end{aligned} \quad (7)$$

<sup>#2</sup> Of course, the scale invariance would be broken at the loop level, as will be addressed below.

with the masses of the mass eigenstate vectors ( $m_{\tilde{V}}, m_{\tilde{W}}$ ).

The new vector boson  $V$  thus does not decay to the weak bosons in association with the Higgs in the presence of the scale/conformal symmetry (*Conformal Barrier*), i.e.,

$$V - W/Z - H \text{ coupling} = 0, \quad (8)$$

consequently the  $V$  predominantly decays to the weak boson pairs  $WW/WZ$ . The absence of  $V \rightarrow WH/ZH$  signatures at the LHC Run-II could indirectly probe the existence of the (approximate) scale/conformal invariance.

The conformal/scale-invariant limit ( $m_V^2 \rightarrow 0$  in Eq.(2)) with the strong coupling ( $g_V \gg 1$ ) is perfectly consistent with the mass  $m_{\tilde{V}} \simeq g_V v \simeq 2$  TeV <sup>#3</sup>, in a way incompatible with the so-called ‘‘equivalence theorem’’ for the  $V \rightarrow WW/WZ$  and  $V \rightarrow WH/ZH$  decays, i.e.,  $\Gamma(V \rightarrow WW/WZ) \simeq \Gamma(V \rightarrow WH/ZH)$ , which actually can only be achieved by taking a special limit  $m_V \gg g_V v (\gg g_W v)$ .

The conformal/scale invariance should be approximate, hence the conformal barrier will be broken at higher order level of the perturbation theory. If the symmetry is explicitly broken only by the Higgs mass term  $\frac{1}{2} m_\phi^2 \phi^2$  (soft-breaking) <sup>#4</sup>, then the trilinear Higgs coupling proportional to the Higgs mass would give rise to the  $\tilde{V}$ - $\tilde{W}$ - $\phi$  at the two loop level, which is, however, too tiny to be detected at the LHC experiments.

To see the conformal/scale invariance more manifestly, we may rewrite the Lagrangian  $\mathcal{L}_V|_{m_V=0}$  in Eq.(6) into the nonlinear realization for the conformal/scale symmetry by introducing the nonlinear base  $\chi = e^{\phi/v} = 1 + \phi/v + \dots$  as

$$\begin{aligned} \mathcal{L}_V \Big|_{m_V=0} &= \frac{1}{2} \chi^2 \mathbf{V}_\mu^T \begin{pmatrix} g_V^2 c_{VVHH} v^2 & \frac{1}{4} g_W g_V c_H v^2 \\ \frac{1}{4} g_W g_V c_H v^2 & \frac{1}{4} g_W^2 v^2 \end{pmatrix} \mathbf{V}^\mu \\ &+ \dots \end{aligned} \quad (9)$$

<sup>#3</sup> It implies a large coupling  $g_V \sim 10$ , which would lead to sizable corrections through the new vector boson loops to other couplings, say, higgs self-couplings. The size of such loop corrections would be quite large ( $\mathcal{O}(g_V^4/(4\pi)^2) = \mathcal{O}(10^2)$ ), implying that the naive perturbation in  $g_V$  would break down, which needs some ultraviolet completion like walking technicolor.

<sup>#4</sup> Another explicit breaking for the scale symmetry would arise as the usual trace anomaly term like the Higgs-diphoton coupling of  $\phi F_{\mu\nu}^2$  form. Since the new vector boson mass arises only from the electroweak scale  $v$  in the presence of the conformal barrier ( $m_V = 0$ ), the charged new vector boson would then contribute to  $\phi F_{\mu\nu}^2$  as a nondecoupling effect, to be strongly constrained by current precise measurements of the Higgs-diphoton coupling at LHC. However, the vector boson loop corrections would be nonperturbative because of the large coupling  $g_V \sim 10$  (See also footnote #3), so that some ultraviolet completion is needed to properly estimate the size of the corrections, as done in the scenario of the walking technicolor.

The form of this Lagrangian implies that the Higgs  $\phi$  is nothing but a dilaton, transforming as  $\delta\phi(x) = (v + x^\nu \partial_\nu \phi(x))$  and  $\delta\chi(x) = (1 + x_\nu \partial^\nu)\chi(x)$ , where the  $v$  is identified with the dilaton decay constant  $F_\phi = v$ .

Actually, the decay constant of the dilaton is not necessarily equal to the  $v$  ( $\chi = e^{\phi/F_\phi}$  with  $F_\phi \neq v$ ): the most general vector boson action invariant under the conformal/scale invariance is given by the scale-invariant version of the hidden local symmetry (sHLS) Lagrangian [31–34],

$$\mathcal{L}_{\text{sHLS}} = \chi^2 F_\pi^2 \left( \text{tr}[\hat{\alpha}_{\mu\perp}^2] + a \text{tr}[\hat{\alpha}_{\mu||}^2] \right) + \dots, \quad (10)$$

where  $\hat{\alpha}_{\perp,||} = (D_\mu \xi_R \xi_R^\dagger \mp D_\mu \xi_L \xi_L^\dagger)/(2i)$  with  $D_\mu \xi_{R,L} = \partial_\mu \xi_{R,L} - iV_\mu \xi_{R,L} + i\xi_{R,L} \mathcal{R}_\mu(\mathcal{L}_\mu)$ . The nonlinear bases  $\xi_R$  and  $\xi_L$  for the chiral  $SU(N_F)_L \times SU(N)_R$  symmetry form the chiral field  $U$  as  $U = \xi_L^\dagger \xi_R$ , which transforms as  $U \rightarrow g_L \cdot U \cdot g_R^\dagger$  with the electroweak gauges partially embedded in  $g_L$  and  $g_R$  as well as the standard-model gauge bosons in the gauge fields  $\mathcal{L}_\mu$  and  $\mathcal{R}_\mu$ . The new vector bosons ( $V_\mu$ ) have been introduced as gauge bosons of the HLS. The decay constant  $F_\pi$  is related to the electroweak scale  $v$  as  $F_\pi^2 = v^2/(N_F/2)$  and the arbitrary parameter  $a$  can be phenomenologically fixed.

To make a direct comparison with the scale-invariant HVT model in Eq.(9), we shall take  $N_F = 2$  and expand the sHLS Lagrangian to get the mass matrix for the electroweak bosons  $W_\mu$  and the new vector bosons  $V_\mu$  ( $\mathbf{V}_\mu = (V_\mu, W_\mu)^T$ ):

$$\mathcal{L}_{\text{sHLS}} = \frac{1}{2} \chi^2 \mathbf{V}_\mu^T \begin{pmatrix} a g^2 v^2 & -\frac{a}{2} g g_W v^2 \\ -\frac{a}{2} g g_W v^2 & \frac{(1+a)}{4} g_W^2 v^2 \end{pmatrix} \mathbf{V}_\mu + \dots, \quad (11)$$

where we have introduced the new-vector boson kinetic term ( $-\frac{1}{2g^2} \text{tr}[V_{\mu\nu}^2]$ ) with the gauge coupling  $g$  and rescaled the vector fields canonically. It is obvious that the mass matrix and the vertices involving the Higgs = dilaton  $\phi$  are simultaneously diagonalized away in the same way as in Eq.(11): the conformal/scale symmetry prohibits the new vector boson  $V$  from decaying to the Higgs.

Conversely, if the decay of new vector bosons into the Higgs is not observed in the ongoing Run II of the LHC, then it is suggested that the Higgs is a dilaton.

The sHLS Lagrangian in Eq.(10) is the effective theory realizing the (approximate) scale/conformal invariance and chiral symmetry of the underlying theory, the walking technicolor [23]. In the walking technicolor, the Higgs is nothing but the technidilaton ( $\phi$ ), a composite pseudo Nambu-Goldstone boson for the (approximate) conformal/scale symmetry, and the new vector bosons are the technirhos ( $V$ ). The conformal/scale symmetry of the sHLS is explicitly broken by the dilaton mass in the potential of the form  $\sim F_\phi^2 m_\phi^2 \chi^4 (\log \chi - 1/4)$ ,

which corresponds to the trace anomaly of the underlying walking technicolor. The effect of the symmetry breaking arises only at  $\mathcal{O}(p^6)$  or higher orders of the derivative expansion, since the  $\mathcal{O}(p^4)$  terms are already scale-invariant without involving the technidilaton field  $\chi = e^{\phi/F_\phi}$ . Thus, additional Higgs (=  $\phi$ ) potential terms are not generated at the  $\mathcal{O}(p^4)$ . Though the dilaton decay constant  $F_\phi$  is in principle determined from the walking dynamics itself, the value of  $F_\phi$  can be fitted to the LHC Higgs coupling data [24–29], while the diboson channels are totally blind against the  $F_\phi$  because of the absence of the  $V \rightarrow W\phi/Z\phi$  modes <sup>#5</sup>.

In Ref. [5] it is shown that the 2 TeV technirho can explain the ATLAS diboson excesses. Although in Ref. [5] the one-family model is taken as a realistic walking technicolor, the actual analysis of diboson events is free from the model-dependent parameters  $a$  and  $F_\phi$ . The absence of the  $W\phi$  and  $Z\phi$  channels thus leads to the significantly large  $V \rightarrow WW/WZ$  cross sections, compared to other types of vector bosons (e.g.,  $W'/Z'$ ) without the scale invariance [6–19]. Hence the diboson excesses can naturally be explained by the 2 TeV technirho <sup>#6</sup>. The vector boson model [36], on which the diboson analysis in Ref. [6] has been based, can be transformed into the HVT model in Eq.(1). If the (approximate) conformal/scale invariance is present in the underlying theory such as the walking technicolor, leading to the effective model in Ref. [36], then the matrix of the  $V$ - $W$ - $\phi$  vertices are diagonalized simultaneously with the vector boson mass matrix. Consequently, the same argument as the above becomes applicable to the model in [36].

One way out to avoid the conformal barrier may be to introduce multi Higgs fields which give the masses to new vector bosons as well as the weak bosons. The mixing among the Higgs bosons would make the mixing structures different for the  $V$ - $W$  and  $V$ - $W$ - $\phi$ . Models having such a vector boson - Higgs boson sector correspond to those studied in Refs. [17, 18]. However, some of those Higgs bosons would phenomenologically be heavy to be integrated out, such that, except the lightest 125 GeV Higgs, all the Higgs fields in the linear realization can be cast into the nonlinear forms keeping only the Nambu-Goldstone boson fields (nonlinear realization). The aforementioned models will then be effectively described as a model having the lightest Higgs and multi Nambu-

<sup>#5</sup> In this respect, the analysis in Ref. [35] is subject to modifications, which will be given in another communication. Especially, there are no couplings between  $\phi$ , gluon  $g$  and color-octet technirhos.

<sup>#6</sup> As noted in Ref. [5], the narrowness reported from the ATLAS group on the 2 TeV resonance (with the width  $< 100$  GeV) can be ensured by a suppression factor by  $N_F$  characteristic to the one-family model with  $N_F = 8$ , compared to the rho meson width in the naive-scale up of QCD with  $N_F = 2$ .

Goldstone bosons eaten by weak and new vector bosons (or some of them would be real electroweak pions such as technipions). Then, the conformal barrier would be operative even for such those multi Higgs models.

In conclusion, we have proposed novel handcuffs for new vector bosons in consequence of the presence of the (approximate) conformal/scale invariance: conformal/scale symmetry prohibits new vector bosons decay to the Higgs. The LHC Run-II may probe the presence of the conformal/scale invariance hidden in the underlying theory responsible for the existence of new vector bosons: conversely, if the decay of new vector bosons into the Higgs is not observed in the ongoing LHC Run-II, then the Higgs can be a dilaton.

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